# Configuration and Mission Aspects of Passive Recovery System for Payload

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## Nomenclature

| | |
|---|---|
| $C_D$ | Coefficients of drag |
| $H$ | Enthalpy, J/kg |
| $I_{xx}$, $I_{yy}$, $I_z$ | Moments of inertia, kg-$m^2$ |
| $I_{xy}$, $I_{yz}$, $I_{zx}$ | Products of inertia, kg-$m^2$ |
| Le | Lewis number |
| $M$ | Mach number |
| $p$, $q$, $r$ | Body rates, deg/s |
| $P$ | Pressure, Pa |
| Pr | Prandtl number |
| $q$ | Dynamic pressure, kPa |
| $q_c$ | Convective heat transfer rate, W/$cm^2$ |
| $R_N$ | Nose radius, m |
| $T$ | Temperature, K |

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| | |
|---|---|
| $V$ | Velocity, m/s |
| $u$, $v$, $w$ | Relative velocity components in body frame (m/s) |
| $\sum F_{XB}, \sum F_{YB}, \sum F_{ZB}$ | Sum of all the forces acting on the body in $X$, $Y$ & $Z$-direction |
| $\sum M_{XB}, \sum M_{YB}, \sum M_{ZB}$ | Sum of all the moments acting on the body in $X$, $Y$ & $Z$-direction |

## Subscript

| | |
|---|---|
| $\infty$ | Free stream condition |
| DT | Dissociation of gas mixture |
| $T$ | Total condition |
| $W$ | Wall condition |

## 1 Introduction

One of the feasible options to ensure low cost access to the space is recovery of the spent stages/payload after completion of their intended role and reuse the same for multiple times with minimum turnaround time. Major recovery configuration options are winged body landing on runway, vertical landing with retro burning and splash down with minimum impact velocity based on aerodynamic decelerator. Three different kinds of aerodynamic decelerator exist, namely mechanically deployable aerodecelerator, parachute system and Inflatable Aerodynamic Decelerator system (IAD).

Sounding rockets are having inherent characteristics of lower cost, short lead time and ability to reach higher altitudes where balloons and satellites are inoperative. Sounding rockets are having passive control with spin stabilized. The present stage and payload are expendables. Studies are being carried out for recovery of payload as a first step towards the recovery of stage. This paper mainly addresses recovery of a payload from sounding rocket experiment using Inflatable Aerodynamic Decelerator. This paper briefly explains IAD configuration, mission design, structure construction and aerothermal analysis and material selection for IAD.

## 2 Configuration

The typical Mach number versus the drag coefficient of sphere cone, tension cone, isotensoid and parachute is as shown in Fig. 1. Figure 1 is taken from Ian G. Clark, Allison L. Hutchings, Christopher L. Tanner, Robert D. Braun.: Supersonic Inflatable

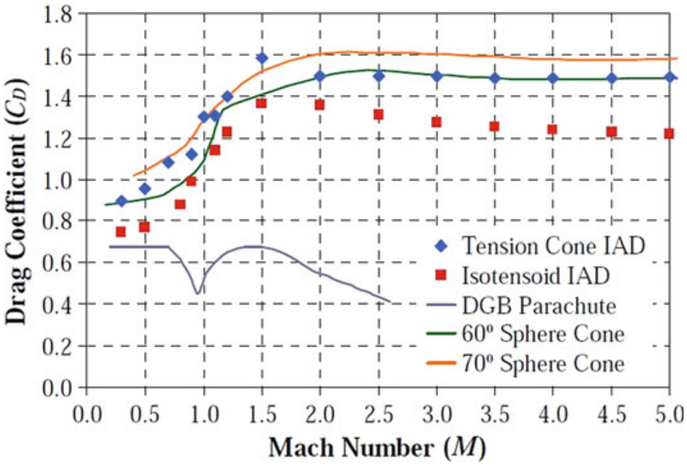

**Fig. 1** Mach number versus drag coefficient for various inflatable decelerator configurations [1]

Aerodynamic Decelerators For Use on Future Robotic Missions to Mars paper [1]. Figure 1 depicts that 70° sphere cone configuration provides higher drag coefficient compared to other configurations.

The sphere cone configuration with a flare angle of 70° is chosen for considering higher drag coefficient during supersonic as well as subsonic regime. Figure 2 depicts configuration and parameters such as forward radius (Ra), base radius (Rb) and torus radius (Rt) arrived to meet the required ballistic coefficients. The deployed IAD is statically stable, which will re-orient itself and flow will be facing the forward region. Configuration parameters are varied to achieve the ballistic coefficients ($\beta$ or beta) of 15, 30 and 42.5 kg/m$^2$ with payload mass of 50 kg.

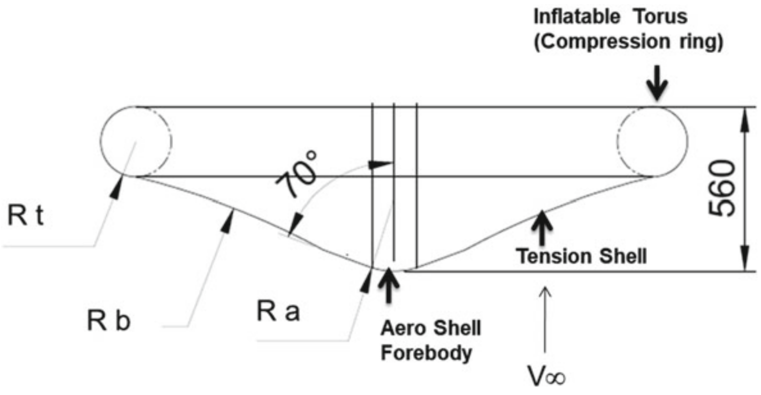

**Fig. 2** Schematic IAD configuration

## 3 Mission Design

Mission objectives are functioning inflatable system such as aeroshell and compression ring at higher altitude, self re-orientation of IAD and touch-down velocity that should be less than 20 m/s.

Sounding rocket configurations are sized to statically stable even under performance deviations. Sounding rockets are unguided, uncontrolled and fin stabilized. Sounding rockets spinning are provided by spin rockets and then sustained due to aerodynamics of canted fin. Sounding rocket (RH-300) is a single-stage configuration, and the payload compartment is located on top of solid booster. Overall vehicle length is 5.9 m, diameter is 0.31 m, and gross mass of 500 kg with payload capability is 50 kg. Aeroshell and compression ring along with payload are in stowed condition and placed in payload compartment.

The equations of motion are solved to determine the state vectors at any instant. Equations of motion in the body frame of the vehicle are as follows.

$$m(\dot{u} - rv + qw) = \Sigma F_{XB} \tag{1}$$

$$m(\dot{v} - pw + ru) = \Sigma F_{YB} \tag{2}$$

$$m(\dot{w} - qu + pv) = \Sigma F_{ZB} \tag{3}$$

$$I_{xx}\dot{p} + (r^2 - q^2)I_{yz} + rq(I_{zz} - I_{yy}) + (rp - \dot{q})I_{xy} - (\dot{r} + pq)I_{zx} = \Sigma M_{XB} \tag{4}$$

$$I_{yy}\dot{q} + (p^2 - r^2)I_{zx} + pr(I_{xx} - I_{zz}) + (pq - \dot{r})I_{yz} - (\dot{p} + qr)I_{xy} = \Sigma M_{YB} \tag{5}$$

$$I_{zz}\dot{r} + (q^2 - p^2)I_{xy} + pq(I_{yy} - I_{xx}) + (qr - \dot{p})I_{zx} - (\dot{q} + rp)I_{yz} = \Sigma M_{ZB} \tag{6}$$

Using these equations, vehicle translation and rotational motion are determined considering all external forces and moments acting on the body.

Trajectory studies are carried out for sounding rocket (RH 300), and various trajectory parameter profiles are shown in Fig. 3. The payload reaches a peak altitude of around 90 km with help of sounding rocket and descends after accomplishing experiments, and then payload experiences higher dynamic pressure of 180 kPa at an altitude of 18 km as shown in Fig. 3. Hence, IAD deployment is scheduled at an altitude of 45 km, where sensible atmosphere exists to enhance the performance of aerodynamic decelerator and thereby dynamic pressure of the payload can be reduced significantly. Aeroshell and compression ring are deployed by injecting the inflate gas from the gas bottle. IAD will self re-orient due to monostability of the configuration and re-enters into the dense atmosphere with flow phasing towards large radius as shown in Fig. 4, which will result large aerodynamic drag, thereby

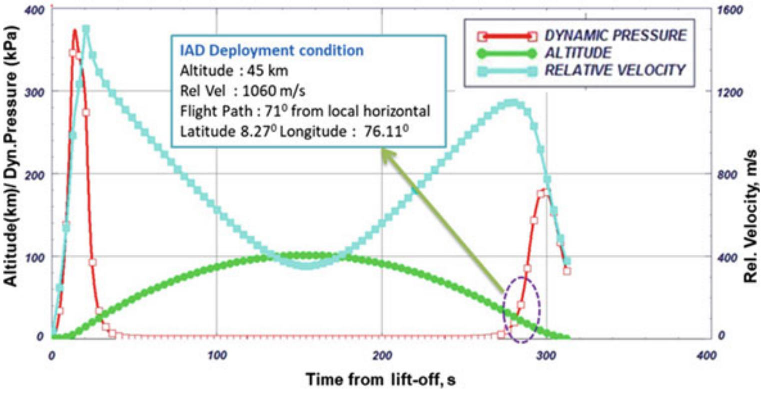

**Fig. 3** Trajectory parameters for sounding rocket (RH300)

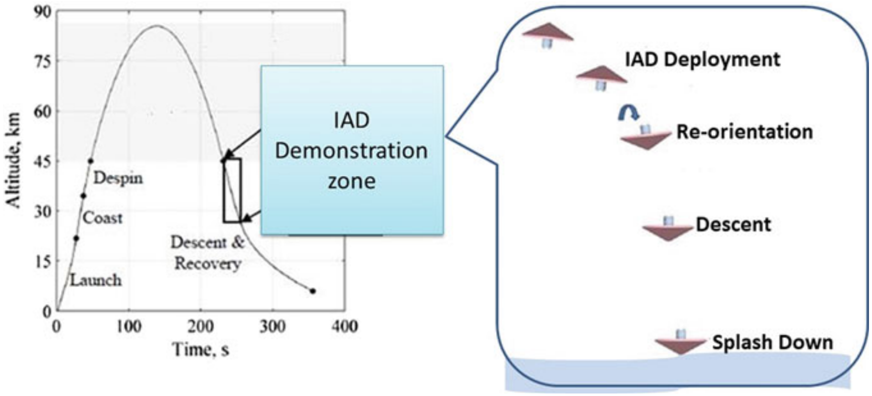

**Fig. 4** Typical mission profile of sounding rocket and IAD deployment sequence

higher velocity reduces and makes soft landing without a retro brake or parachute due to ballistic coefficients.

In order to achieve the minimum touch-down speed, the various ballistic coefficients of 42.5, 30, 15 kg/m$^2$and without IAD are configured by increasing the size of IAD and total mass of 50 kg is fixed. Mission studies are carried out from peak altitude of 90 km to till touch-down phase. From Fig. 5, trajectory parameter indicates that dynamic pressure and touch-down velocity reduce by one order compared to without IAD configuration. As ballistic coefficients decrease, dynamic pressure and impact velocity also decrease, but the flight duration increases. The ballistic coefficient of 15 kg/m$^2$ attains the touch-down speed of 16 m/s.

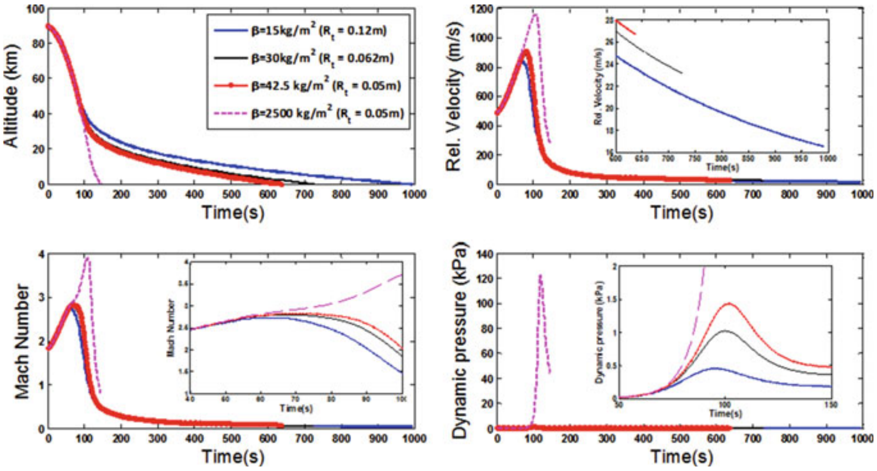

**Fig. 5** Trajectory parameter profiles of payload with IAD for various ballistic coefficients

## 4 Structure Construction

Aeroshell is constructed as thin membrane made of ZYLON filament textile. Hemisphere is constructed as aluminium cover to hold the aeroshell. Six ribs are provided at the rear side to enhance the stability. All of the electrical device and gas injection systems are installed. Pyrotechnic cutters are used to inflation system to release pressurized gas. Internal inflation system provides gas to decelerator, and IAD system is filled with an internal pressure of 1.4 bar.

## 5 Aerothermal Analysis

Aerodynamic heating analysis is carried out for the IAD configuration. Heating rates at the minimum radii locations are estimated using Fay and Riddell correlation [2].

$$q_c = 0.763(\rho_T\mu_T)^{0.4}(\rho_w\mu_w)^{0.1}\left[1+\left(L_e^{0.52}-1\right)\frac{H_{D,T}}{H_T}\right]\left(\frac{\mathrm{d}u}{\mathrm{d}x}\right)^{0.5}\mathrm{Pr}^{-0.663}H_T - H_w$$

$$\text{Velocity gradient}\left(\frac{\mathrm{d}u}{\mathrm{d}x}\right) = \frac{1}{R_N}\sqrt{\frac{2(P_{T\_}P_\infty)}{\rho_T}} \text{ for } M_\infty \geq 1$$

$$\left(\frac{\mathrm{d}u}{\mathrm{d}x}\right) = \frac{3V_\infty}{2R_N} \text{ for } M_\infty < 1$$

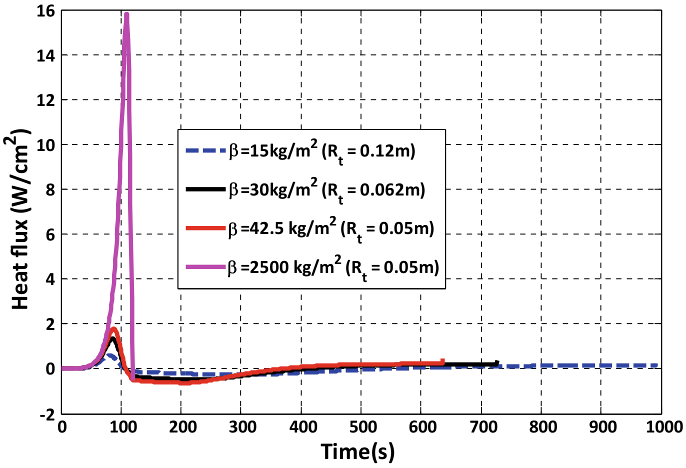

**Fig. 6** Heat flux histories of payload with IAD for various ballistic coefficients

Heat flux histories for various ballistic coefficients configurations are estimated and shown in Fig. 6. The maximum heat flux of 1.8 W/cm$^2$ is observed, and ZYLON-based materials are selected which can withstand temperature of 100 °C. Thermal analysis is also carried out, and surface reaches the maximum temperature of 60 °C.

## 6 Summary

Inflatable Aerodynamic Decelerator of 70° sphere cone configuration is worked out for the total mass of 50 kg, and configuration is having merits of higher drag for all the speed regimes. Detailed mission studies are carried out by varying the ballistic coefficients and respective configurations to achieve the minimum touch-down speed of 16 m/s. Preliminary structural construction and aerothermal analysis are carried out. Aluminium is chosen for hemispherical region, and ZYLON-based composite material is chosen for aeroshell.

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